Electron spin qubits in quantum dots

R. Hanson, J.M. Elzerman, L.H. Willems van Beveren, L.M.K. Vandersypen, and L.P. Kouwenhoven[1]

[1]*Kavli Institute of NanoScience Delft, Delft University of Technology,*
PO Box 5046, 2600 GA Delft, The Netherlands

(Dated: September 24, 2004)

We review our experimental progress on the spintronics proposal for quantum computing where the quantum bits (qubits) are implemented with electron spins confined in semiconductor quantum dots. Out of the five criteria for a scalable quantum computer, three have already been satisfied. We have fabricated and characterized a double quantum dot circuit with an integrated electrometer. The dots can be tuned to contain a single electron each. We have resolved the two basis states of the qubit by electron transport measurements. Furthermore, initialization and single-shot read-out of the spin state have been achieved. The single-spin relaxation time was found to be very long, but the decoherence time is still unknown. We present concrete ideas on how to proceed towards coherent spin operations and two-qubit operations.

PACS numbers:

INTRODUCTION

The interest in quantum computing [1] derives from the hope to outperform classical computers using new quantum algorithms. A natural candidate for the qubit is the electron spin because the only two possible spin orientations $|\uparrow\rangle$ and $|\downarrow\rangle$ correspond to the basis states of exactly one qubit. The Zeeman splitting, ΔE_Z, between the two basis states is given by $\Delta E_Z = g\mu_B B$, with g the electron g-factor, μ_B the Bohr magneton and B the magnetic field. We follow the proposal by Loss and DiVincenzo to use electron spins confined in semiconductor quantum dots [2].

The quantum dots are defined in a GaAs/AlGaAs two-dimensional electron gas (2DEG) by applying negative voltages to metallic surface gates [3]. These structures offer high flexibility and tunability, and allow easy integration with other devices, such as spin filters and electrometers. Measurements are performed in a dilution refrigerator with base temperature $T = 10$ mK, where we can apply static magnetic fields up to 15 T.

We consider the five criteria of DiVincenzo's checklist [4] which must *all* be satisfied for any physical implementation of a quantum computer. We review the experimental progress on the spin qubit proposal using these five criteria in the sections below.

I: SCALABLE PHYSICAL SYSTEM WITH WELL-CHARACTERIZED QUBITS

The first of the five DiVincenzo requirements is to have a scalable physical system with well-characterized qubits. We have fabricated a double quantum dot circuit in which a single electron can be confined in each of the two dots [5]. In this circuit, a quantum point contact (QPC) defined close to the dots can be employed as a sensitive electrometer [6, 7]. The structure of the surface gates is depicted in Fig. 1a.

In Fig. 1b we map out the charging diagram of the double dot using the electrometer. Horizontal (vertical) lines in this diagram correspond to changes in the number of electrons in the left (right) dot. In the top right of the figure lines are absent, indicating that the double dot is completely depleted of electrons. Now the absolute number of electrons can be easily determined by counting the number of charge transitions. In the region indicated by "11" both dots contain a single electron.

We use electron transport measurements through a single dot (see Fig. 2a) to resolve the two qubit states $|\uparrow\rangle$ and $|\downarrow\rangle$ [8]. The device is tuned to contain just a single electron. We find a charging energy of 2.4 meV and an orbital level spacing of 1.1 meV at $B = 0$ T. Figs. 2b-d show stability diagrams [3] around the 0↔1 electron transition, measured at $B = 6$ T, 10 T and 14 T. In these diagrams, excited states appear as lines in the differential conductance. A clear Zeeman splitting of both ground and first orbital excited state is seen directly in this spectroscopy measurement. Fig. 2e shows the measured Zeeman splitting for magnetic fields 4-14 T.

Concluding this section, we have fabricated a double dot device with integrated electrometer that can serve as a two-qubit circuit. Scaling up to more qubits is straightforward. Also, we have identified the two basis states and measured the energy splitting between them as a function of magnetic field. Thus, the first requirement is fulfilled.

II: INITIALIZATION

Initialization of the spin to the pure state $|\uparrow\rangle$ – the desired initial state for most quantum algorithms [1] – can be achieved by waiting so long that energy relaxation will cause the the spin on the dot to relax to the $|\uparrow\rangle$ ground state. This is a very simple and robust initialization approach, which can be used for any magnetic field

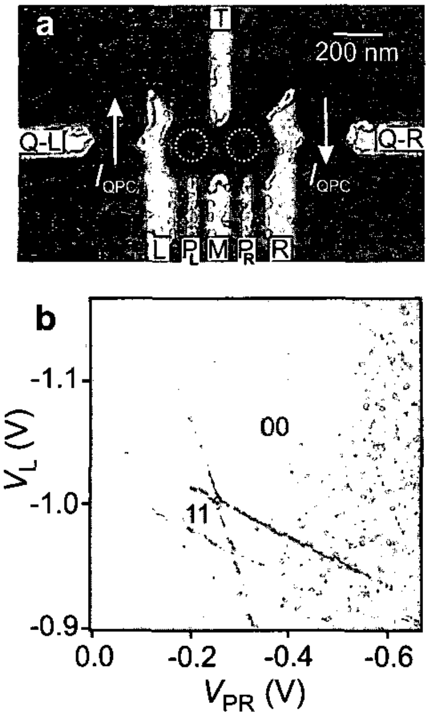

FIG. 1: (a) Scanning Electron Micrograph of the metallic surface gates. White dotted circles indicate the two quantum dots. White arrows show the possible current paths for the QPCs. (b) Charge stability diagram ("honeycomb") of the double quantum dot, measured with Q-R. A modulation (0.3 mV at 17.77 Hz) is applied to gate L, and dI_{QPC}/dV_L is measured with a lock-in amplifier and plotted in grayscale versus V_L and V_{PR}. The lines are due to charge transitions. The label "11" indicates the region where each dot contains one electron. Adapted from Ref. [5].

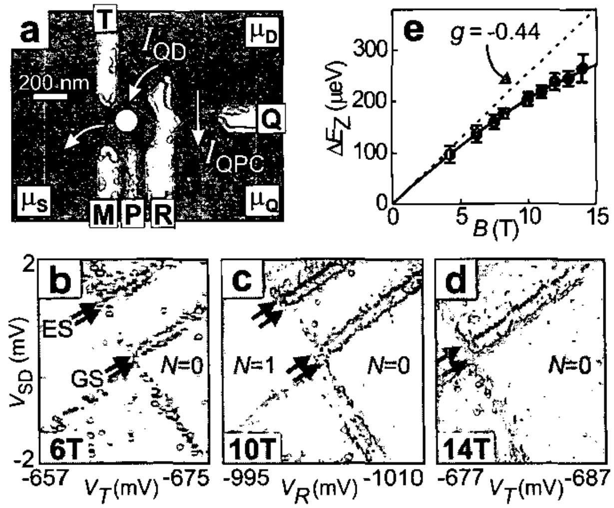

FIG. 2: (a) Scanning Electron Micrograph of the metallic surface gates (for clarity, we have hidden the surface gates that are not used in these experiments). Gates M, R and T are used to form the quantum dot indicated by a white circle. Current through the dot, I_{QD} is measured as a function of applied bias voltage, $V_{SD} = (\mu_S - \mu_D)/e$. (b)-(d) Differential conductance dI_{QD}/dV_{SD} as a function of V_{SD} and gate voltage near the 0$\leftrightarrow$1 electron transition, at parallel magnetic fields of 6, 10 and 14 T. Darker corresponds to larger dI_{QD}/dV_{SD}. The zero-field spin degeneracy of both the ground state (GS) and the first orbital excited state (ES) is lifted by the Zeeman energy as indicated by arrows. (e) Extracted Zeeman splitting ΔE_Z as a function of B. Adapted from Ref. [8].

orientation (provided that $g\mu_B B > 5k_B T$). However, as it takes about $5T_1$ to reach equilibrium, it is also a very slow procedure.

A faster initialization method is to place the level $|\uparrow\rangle$ below and $|\downarrow\rangle$ above the Fermi energy of the leads (as in Fig. 3a). Then, a spin-up electron will stay on the dot, whereas a spin-down electron will tunnel out to the leads, to be replaced by a spin-up. After waiting a few times the sum of the typical tunnel times for spin-up and spin-down ($\sim 1/\Gamma_\uparrow + 1/\Gamma_\downarrow$), the spin will be with large probability in the $|\uparrow\rangle$ state. This initialization procedure is therefore quite fast. In our experiments, both initialization methods have already been used.

We also have the possibility to initialize the dot to a mixed state, where the spin is probabilistically in $|\uparrow\rangle$ or $|\downarrow\rangle$, by first emptying the dot, followed by placing both spin levels below E_F. The dot is then randomly filled with either a spin-up or a spin-down electron. This can be very useful, especially for verifying read-out procedures and testing two-spin operations.

III: QUBIT READ-OUT

Read-out determines the result at the end of the computation by measuring specific qubits. We have achieved single-shot read-out of the spin orientation of an individual electron in a quantum dot [9]. Our approach utilizes the Zeeman splitting, induced by a large magnetic field parallel to the 2DEG, to create spin-to-charge conversion (Fig. 3a). This is followed by real-time detection of single-electron tunneling events using the electrometer. The total visibility of the spin measurement is $\sim$ 65%, limited mostly by the $\sim$ 40 kHz bandwidth of our current measurement setup, and also by thermal excitation of electrons out of the quantum dot, due to the (in this experiment) high effective electron temperature of $\sim$ 300 mK.

We estimate that we can improve the visibility of the spin read-out technique to more than 90% by lowering the electron temperature below 100 mK, and especially by using a faster way to measure the charge on the dot. This could be possible with a 'radio-frequency QPC' (RF-QPC), similar to the well-known RF-SET [10]. In this approach, the QPC is embedded in an LC circuit with

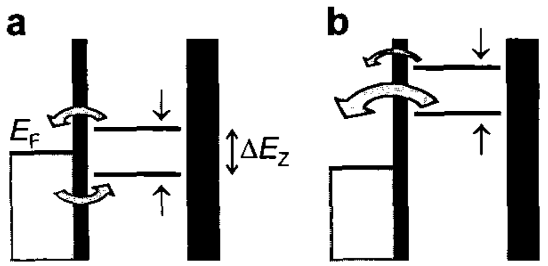

FIG. 3: Schematic energy diagrams depicting spin-to-charge conversion based on a difference in *energy* (a) between $|\uparrow\rangle$ and $|\downarrow\rangle$, or on a difference in *tunnel rate* (b).

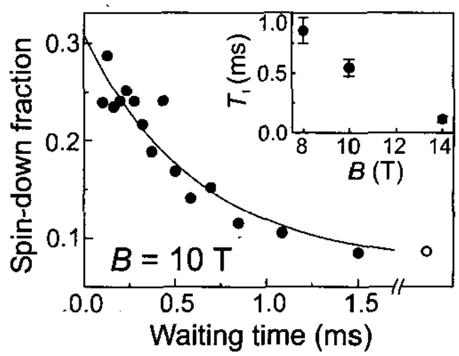

FIG. 4: Spin relaxation: measured fraction of spin-down as a function of the wait time, for an in-plane magnetic field of 10 T. Inset shows the field-dependence of T_1. Adapted from Ref. [9].

a resonant frequency of $\sim$ 1 GHz. By measuring the reflection or transmission of a resonant carrier wave, we estimate that it should be possible to read out the charge state of the nearby quantum dot in $\sim 1\ \mu$s, an order of magnitude faster than is currently attainable.

A different way to perform spin-to-charge conversion is to use not a difference in *energy* between spin-up and spin-down, but a difference in *tunnel rate* (Fig. 3b). To read out the spin orientation of an electron on the dot, we simply raise both dot levels above E_F, so that the electron can leave the dot. If the tunnel rate for spin-up electrons, $\Gamma_\uparrow$, is much larger than that for spin-down electrons, $\Gamma_\downarrow$, then at a suitably chosen time the dot will have a large probability to be already empty if the spin was up, but a small probability to be empty if the spin is down. Measuring the charge on the dot within the spin relaxation time can then reveal the spin state.

IV: LONG COHERENCE TIMES

The long-term potential of GaAs-based quantum dots as electron spin qubits depends crucially on the spin coherence times T_1 and T_2. We have measured the single-spin relaxation time, T_1, using the single-shot read-out method described in the previous section. We find that T_1 can be very long – on the order of 1 ms [9] (see Fig. 4), implying that the spin is only very weakly disturbed by the environment. The dominant relaxation mechanism at large magnetic field is believed to be the coupling of the spin to phonons, mediated by the spin-orbit interaction [11].

The fundamental figure of merit for spin qubits is the decoherence time of a single electron spin in a quantum dot, T_2, which has never been measured. To build a scalable quantum computer, a sufficiently long T_2 (corresponding to more than 10^4 times the gate operation time) is essential in order to reach the 'accuracy threshold'. However, for experiments in the near future, we only need to perform a few spin rotations within T_2, which might already be possible for much shorter T_2, on the order of a μs. This should also be long enough to perform two-spin operations, which are likely to be much faster.

To find the actual value of T_2, the ability to perform coherent spin operations is required. For this, we plan to use the well-known electron spin resonance (ESR) effect. A microwave magnetic field $\vec{B}_{ac}$ oscillating in the plane perpendicular to $\vec{B}$, at a frequency $f = g\mu_B B/h$ (in resonance with the spin precession about $\vec{B}$) causes the spin to make transitions between $|\uparrow\rangle$ and $|\downarrow\rangle$. The choice of B strength is a trade-off between reliable initialization and read-out (strong B is better) and experimental convenience (low f is easier). Properly timed bursts of microwave power tip the spin state over a controlled angle, e.g. 90° or 180°. In order to observe Rabi oscillations, the Rabi period must be at most of the order of the single-spin decoherence time T_2. For a Rabi period of 150 ns, we need a microwave field strength B_{ac} of $\sim$ 1 mT. If T_2 is much longer, there is more time to coherently rotate the spin, so a smaller oscillating field is sufficient.

To detect the coherent oscillations, we plan to combine (pulsed) electron spin resonance with single-shot spin measurement. This allows us to separate the spin manipulation stage (during which the microwaves are on) from the spin read-out stage (without microwaves). In this way, excitation out of the dot is prevented by Coulomb blockade, until spin read-out is initiated. By varying the pulse time of the microwaves and measuring the corresponding probabilities for the electron spin to end up in $|\uparrow\rangle$ or $|\downarrow\rangle$, we can map out the Rabi oscillations and find T_2.

V: A UNIVERSAL SET OF QUANTUM GATES

With a universal set of quantum gates, any quantum algorithm can be implemented by controlling a particular unitary evolution of the qubits. It is sufficient to have single-qubit gates and a universal two-qubit gate (e.g., XOR or square root of SWAP). Single qubit operations are described in the previous section. To build two-qubit gates, one can use the exchange interaction which arises when two neighboring dots are tunnel coupled. If the double dot is filled with two identical spins, the interaction does not change their orientation. However, if the left electron spin starts out being $|\uparrow\rangle$ and the right one $|\downarrow\rangle$, then the states of the two spins will be swapped after a certain time. An interaction active for half this time performs the $\sqrt{\text{SWAP}}$ gate, which has been shown to be universal for quantum computation when combined with single qubit rotations [12]. In fact, the exchange interaction is even universal by itself when the state of each qubit is encoded in the state of three electron spins [13].

The strength $J(t)$ of the exchange interaction depends on the overlap of the two electron wavefunctions, which varies exponentially with the voltage applied to the gate controlling the inter-dot tunnel barrier. By applying a (positive) voltage pulse with a certain amplitude and duration, we can temporarily turn on the exchange interaction, thereby performing a $\sqrt{\text{SWAP}}$ gate. We expect that J may correspond to a frequency of $\sim$ 10 GHz, so two-qubit gates could be performed in $\sim$ 100 ps. A much larger value would not be convenient experimentally, as we would have to control the exact amplitude and duration of the pulse very precisely. On the other hand, a very slow exchange operation would be more sensitive to decoherence resulting from fluctuations in the tunnel rate, due to charge noise.

To explore the operation of the SWAP gate, we only need reliable initialization and read-out, without requiring ESR [2]. Thus, the SWAP gate can already be implemented with the current technology. Imagine qubit 1 is prepared in a pure state $|\uparrow\rangle$ and qubit 2 is prepared in a statistical mixture of $|\uparrow\rangle$ and $|\downarrow\rangle$. Measurement of qubit 1 should then always give $|\uparrow\rangle$, while measurement of qubit 2 should give probabilistically $|\uparrow\rangle$ or $|\downarrow\rangle$. After application of the SWAP gate, in contrast, measurement of qubit 2 should always give $|\uparrow\rangle$, while measurement of qubit 1 should give a probabilistic outcome, thus demonstrating the two-qubit operation.

CONCLUSIONS

We have reviewed our experimental progress towards a scalable quantum computer using electron spins in quantum dots. Already, three of the five DiVincenzo criteria have been satisfied. Concrete ideas for measuring the coherence time (single-qubit rotations) and performing two-qubit operations have been put forward. Our results are very encouraging for future use of electron spins as qubits.

[1] M.A. Nielsen, I.L. Chuang, *Quantum Computation and Quantum Information* (Cambridge U. Press, New York, 2000).

[2] D. Loss and D.P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

[3] L.P. Kouwenhoven, G. Schön, and L.L. Sohn, in *Mesoscopic Electron Transport*, Vol. 345 of *NATO Advanced Study Institute, Series E*, edited by L.L. Sohn, L.P. Kouwenhoven, and G. Schön (Kluwer Academic Publishers, Dordrecht, 1997).

[4] D.P. DiVincenzo, Fortschr. Phys. **48**, 771 (2000).

[5] J.M. Elzerman, R. Hanson, J.S. Greidanus, L.H. Willems van Beveren, S. De Franceschi, L.M.K. Vandersypen, S. Tarucha, and L.P. Kouwenhoven, Phys. Rev. B. **67**, 161308(R) (2003).

[6] M. Field, C. G. Smith, M. Pepper, D. A. Ritchie, J. E. F. Frost, G. A. C. Jones, and D. G. Hasko, Phys. Rev. Lett. **70**, 1311 (1993).

[7] J.M. Elzerman, R. Hanson, L.H. Willems van Beveren, L.M.K. Vandersypen and L.P. Kouwenhoven, Appl. Phys. Lett. **84**, 4617 (2004).

[8] R. Hanson, B. Witkamp, L.M.K. Vandersypen, L.H. Willems van Beveren, J.M. Elzerman, and L.P. Kouwenhoven Phys. Rev. Lett. **91**, 196802 (2003).

[9] J.M. Elzerman, R. Hanson, L.H. Willems van Beveren, B. Witkamp, L.M.K. Vandersypen, and L.P. Kouwenhoven, Nature **430**, 431 (2004).

[10] R.J. Schoelkopf, P. Wahlgren, A.A. Kozhevnikov, P. Delsing, and D.E. Prober, Science **280**, 1238 (1998).

[11] V.N. Golovach, A. Khaetskii, and D. Loss, Phys. Rev. Lett. **93**, 016601 (2004).

[12] G. Burkard, D. Loss, and D.P. DiVincenzo, Phys. Rev. B **59**, 2070 (1999).

[13] D.P. DiVincenzo, D.P. Bacon, D.A. Lidar, and K.B. Whaley, Nature **408**, 339 (2000).